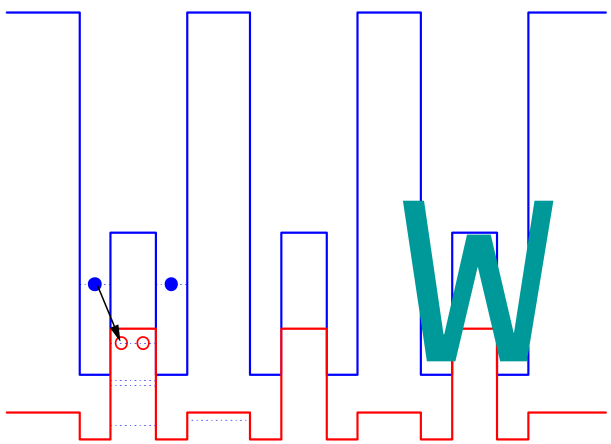
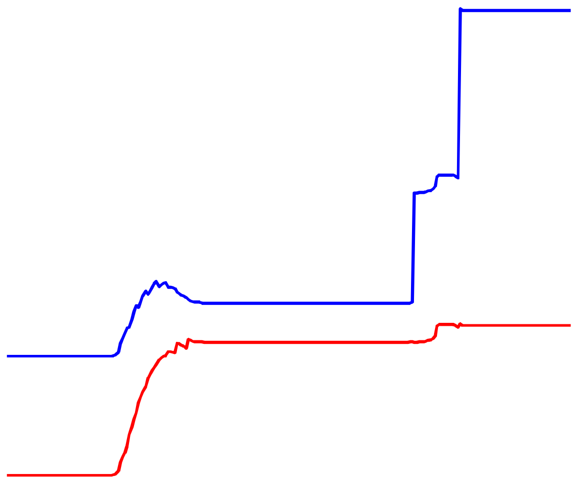
CONTROLLING DARK CURRENT IN TYPE-II SUPERLATTICE PHOTODIODES





Quantum Structures Infrared Photodetectors

(21 January 2009, Yosemite CA)

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OUTLINE

- LWIR detection – Why so challenging, & what key parameters can we improve with electronic & optical engineering?
- “W”-superlattice absorber for LWIR photodiodes
- Graded-gap “W” for LWIR photodiodes
- Hybrid Photodiodes : TSL/GG-W
- Suppression of surface currents
  - Self-passivation by GG-W
  - Shallow-Etch Mesa Isolation (SEMI)

CHALLENGES OF LONG λ DETECTION

- *Significant challenges in growth/processing of MCT and ABSLs*
- *Short lifetime (for thermal generation)*
- *Large thermal population*

$D^* \propto QE/j_D^{1/2}$ $\qquad QE \approx L_d\alpha/(L\alpha+1)$ ①

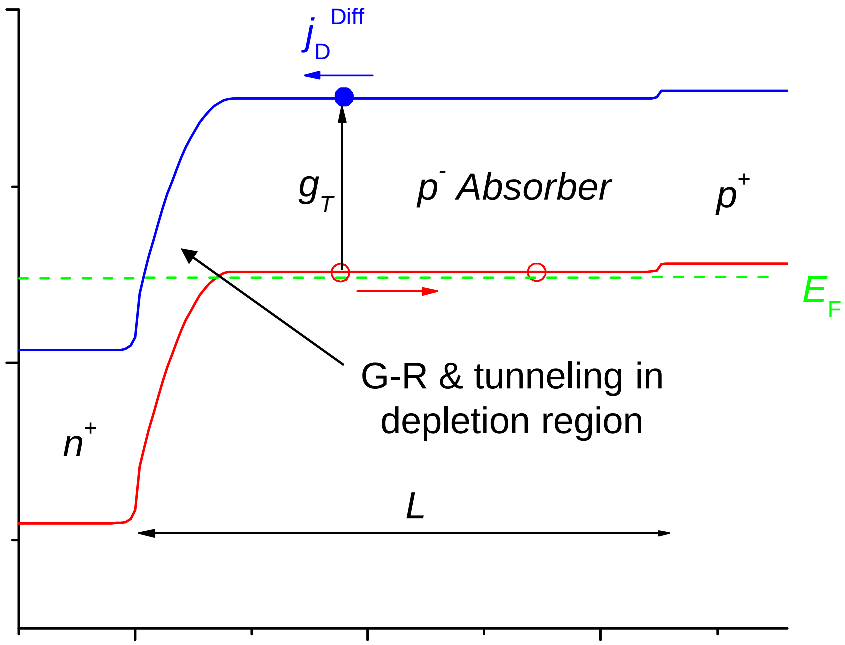
$L_d = (D\tau)^{1/2}$ ③ $\qquad D = k_B T\mu/q$ ②

$j_D \approx j_D^{Diffusion} + j_D^{GR} + j_D^{Tun} + j_D^{Sidewall}$

E.g.: $j_D^{Diff} = qLg_T \rightarrow qLn_i^2/N_A\tau$ ③

$n_i^2 = N_c N_v \exp(-E_g/k_B T)$ ④

At 300 K: >10[18] worse @ 10 μm than 1 μm!



Keys to improved performance:

- $L_d\alpha > L\alpha > 1$ for high QE
- Maximize: ① α, ② μ, ③ τ, & ④ E_g

Because thermal generation rate scales exponentially with E_g, detection is <u>*many*</u> orders of magnitude more challenging in LWIR than NIR

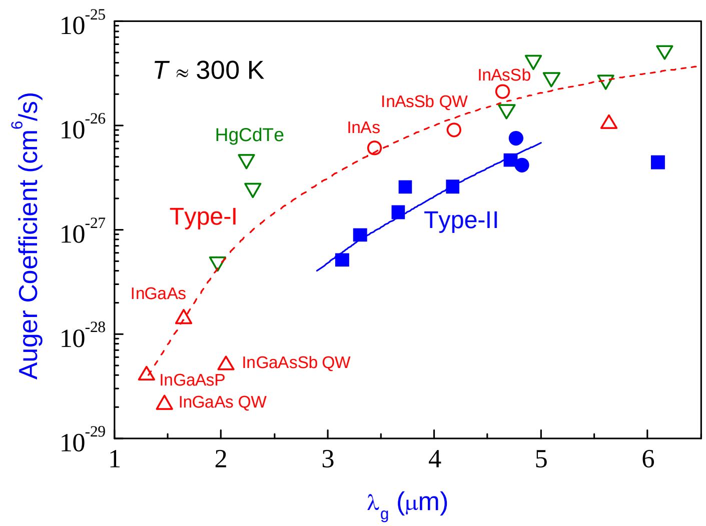
G-R & tunneling currents also scale exponentially with E_g, as does sidewall leakage

DIFFUSION CURRENT: ***MAXIMIZE LIFETIME***

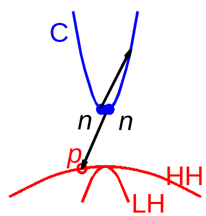
$j_D^{Diffusion} = qLg_T \rightarrow qLn_i^2/N_a\tau$ $\qquad\qquad$ $n_i^2 = N_cN_v exp(-E_g/k_BT)$

Small E_g in absorber is fixed by λ_{co} – So at least maximize τ

Long lifetime minimizes thermal generation rate
(& also maximizes diffusion length for high QE)



- *Auger lifetime:* Enhance with band-structure engineering
  - CCCH processes strongly suppressed because $m_n \approx m_p$



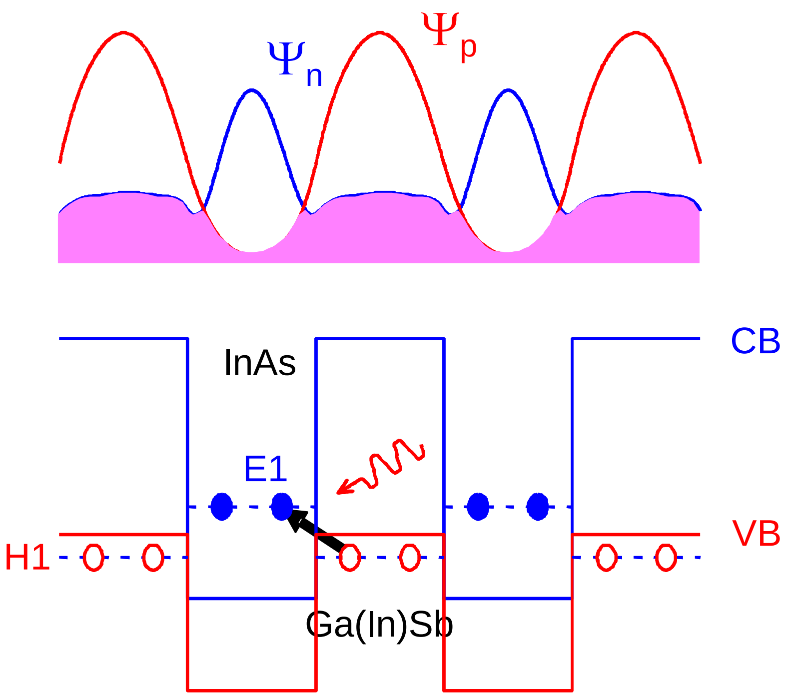
  - Eliminate valence intersubband resonances to suppress CHHH & CHHL (Easier said than done – Band parameters not sufficiently well known)
  - If further suppression is possible, ternary offers more flexibility than binary (whereas growth quality may favor binary)

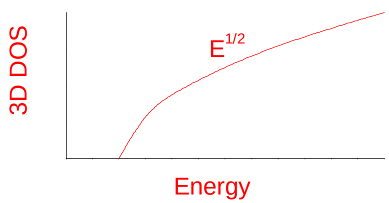
- *Shockley-Read lifetime (typically 10-100 ns):* Key is high MBE quality

ANTIMONIDE "W" DETECTORS

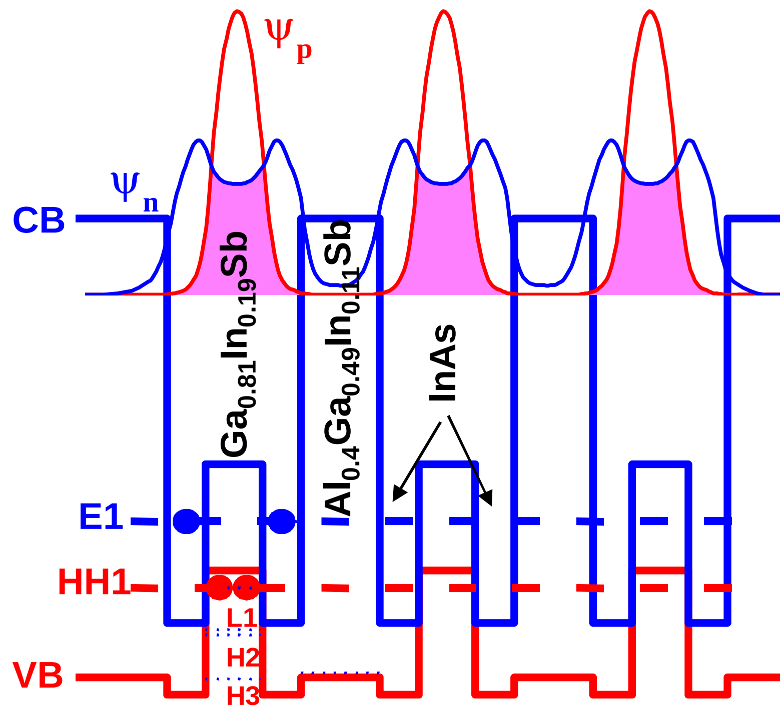
Aifer et al., APL 89, 053519 (2006)

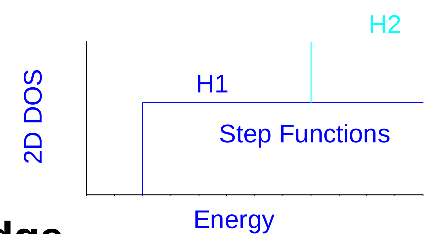
Type II Superlattice (T2SL)





Type-II "W" Superlattice (WSL)





Primary advantages:

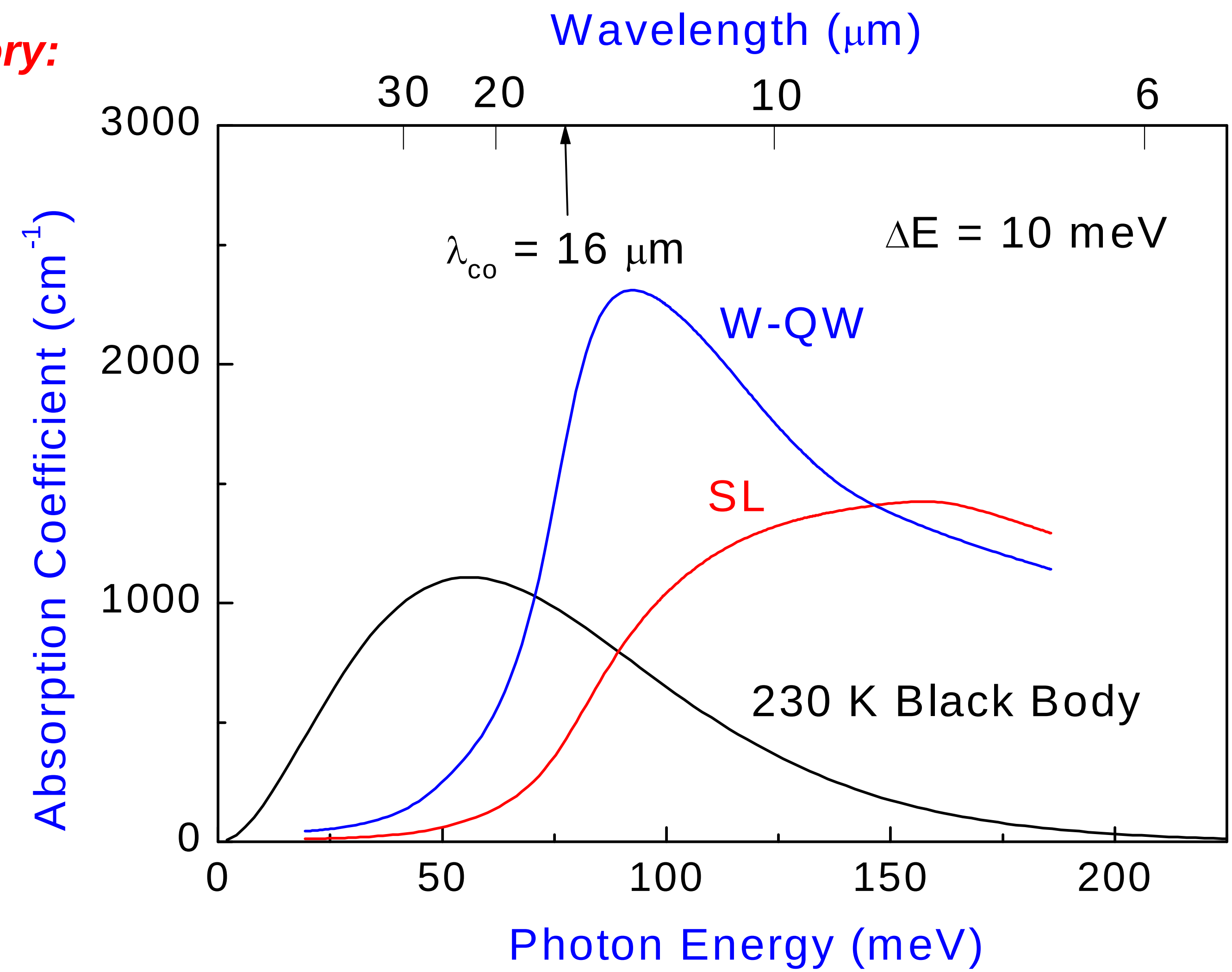
(A). 2D DOS for more abrupt absorption edge

(B). Heavier mass for tunneling suppression

(C). Flexible independent control over CBO & VBO

(A). LARGE DOS FOR STRONG ABSORPTION

Theory:



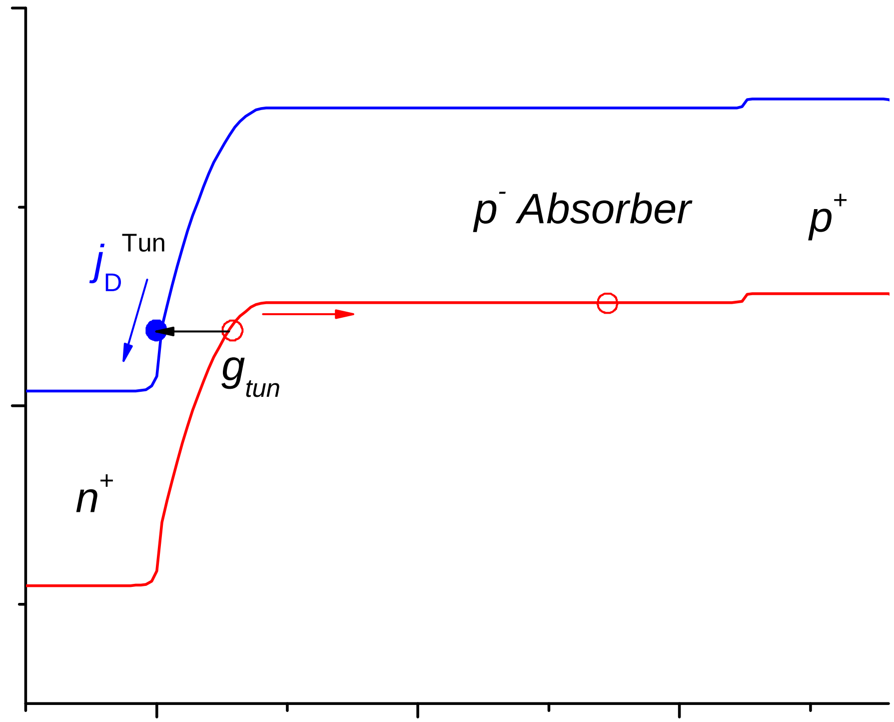
W-QW has much sharper absorption edge than superlattice (Must be careful, because absorption over broad band often more relevant than just at band edge)

(B). TUNNELING SUPPRESSION

$$j_D^{tun} \propto g_{tun} \propto (m_r/E_g)^{1/2}\exp(-Cm_r^{1/2}E_g^{3/2})$$

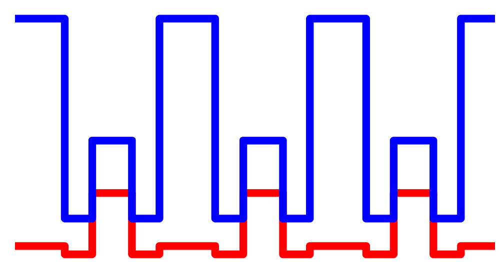
Similar for trap-assisted tunneling, but worse because:

$$E_g \rightarrow E_g - E_t$$



InAs/Ga(In)Sb SL typically has
3 x larger electron mass than HgCdTe

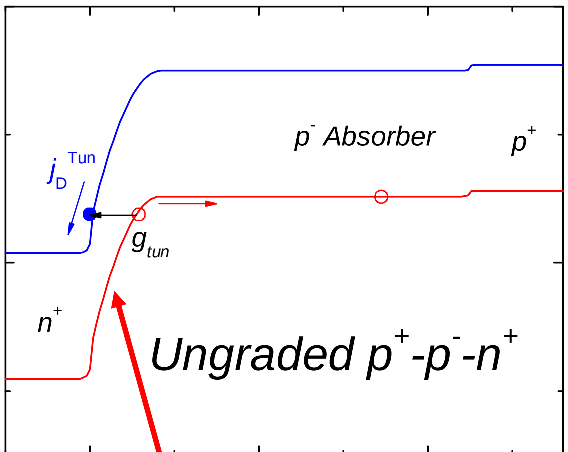
Mass in "W" SL much larger than that, tunable
with barrier thickness



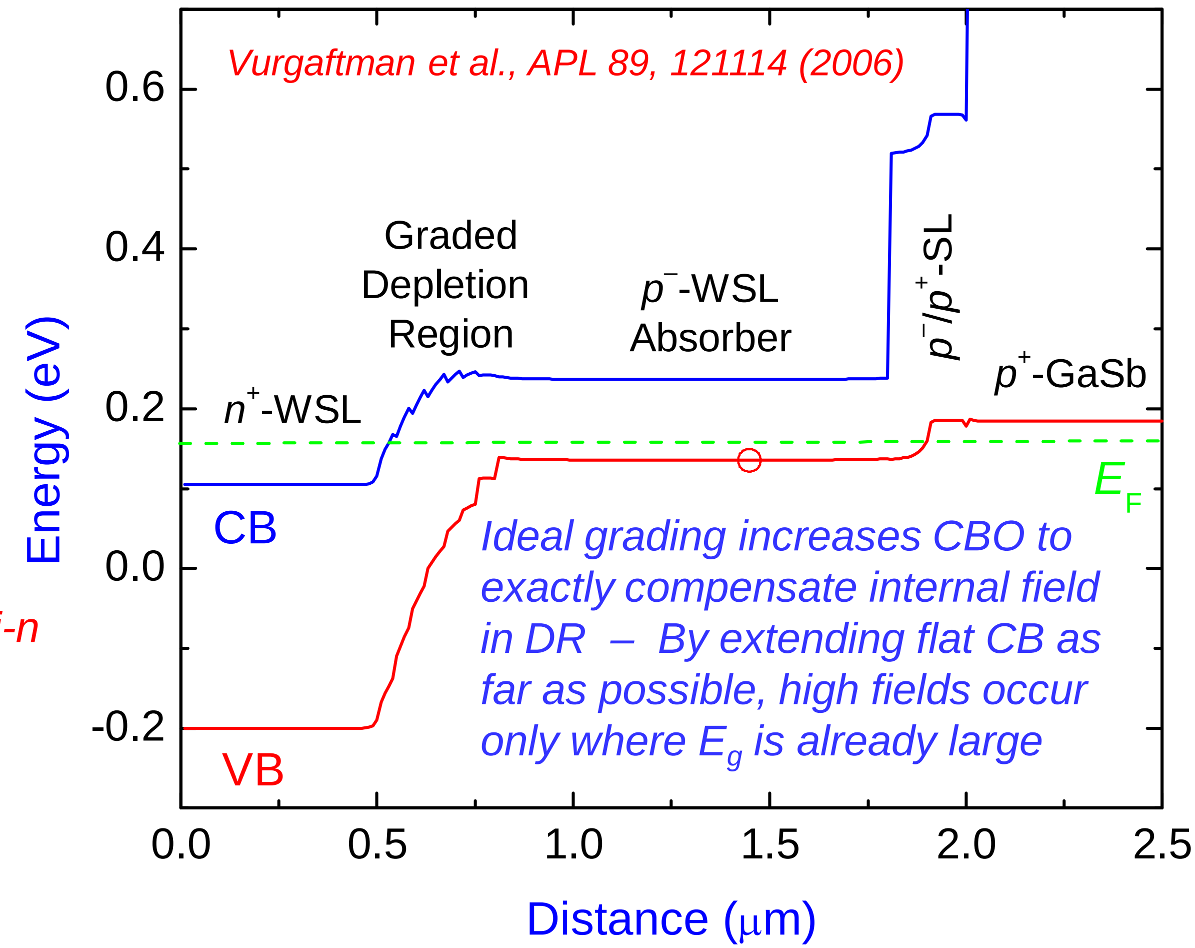
But we can do better!

"W" WITH GRADED-GAP DEPLETION REGION

Need to have a small gap in absorber, *but not everywhere* – Since abrupt shift of E_g would induce large barrier to minority-carrier extraction, *grade the depletion region:*



- *Depletion region of ungraded p-i-n has very high internal fields (mid-10^4 V/cm) – Induces excessive tunneling & G-R*
- *Grading transfers high fields to larger-gap region*

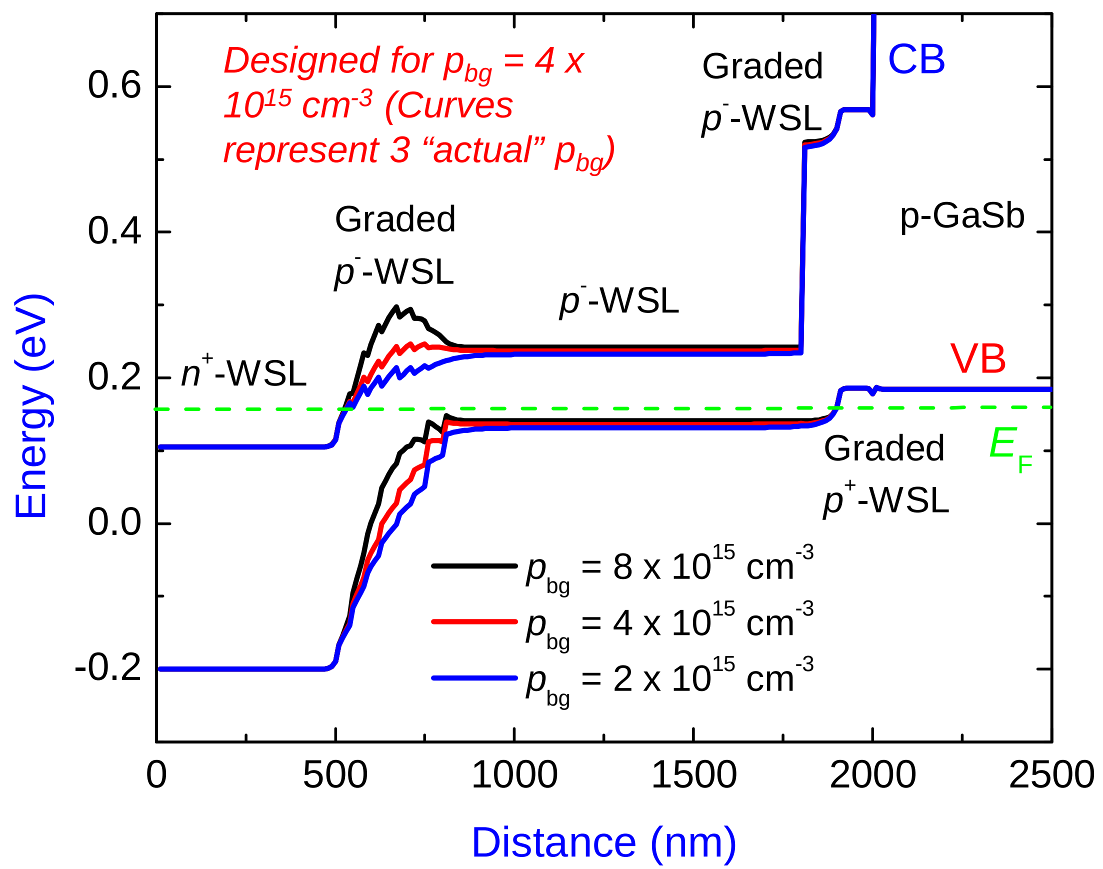


GRADING PROFILES

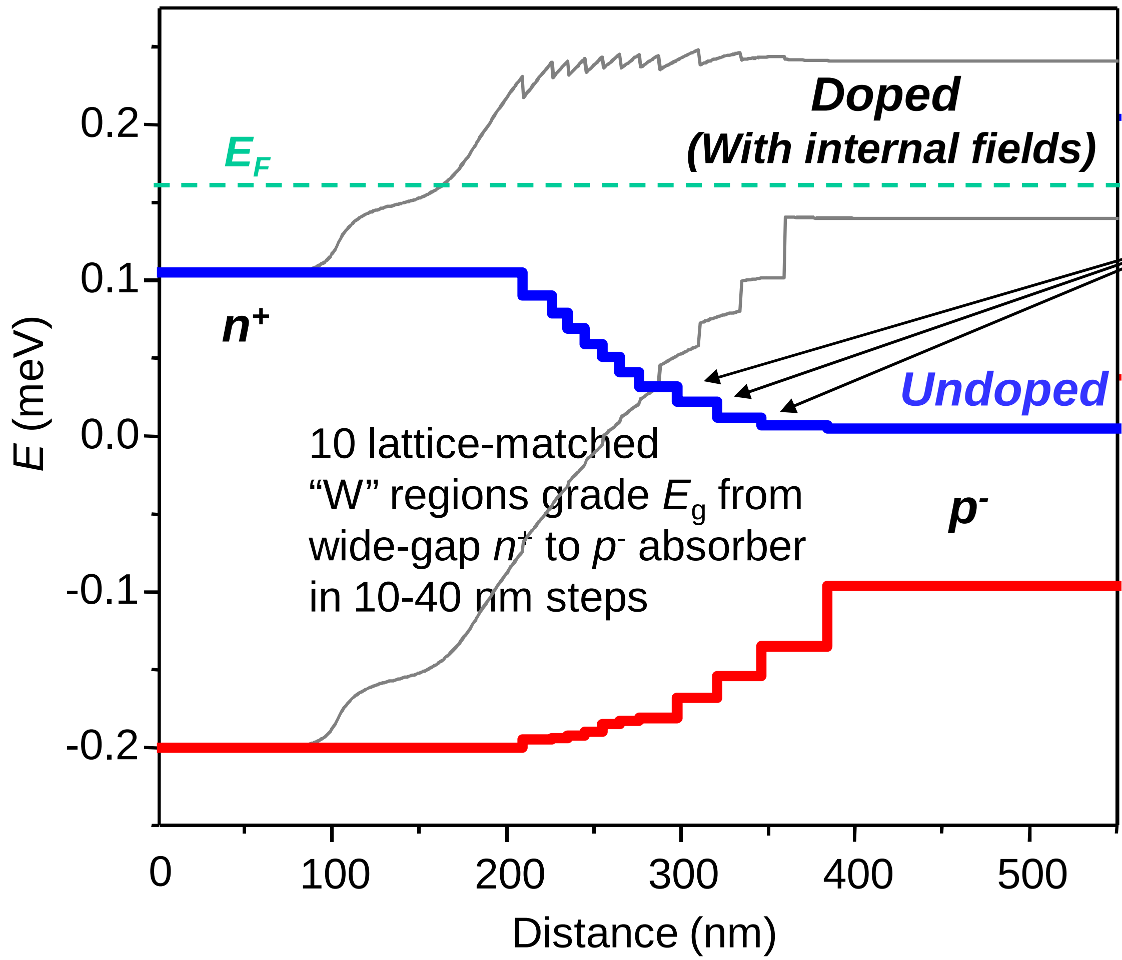
Grading should compensate internal field in depletion region, which is determined by unintentional background p^- doping level (p_{bg})

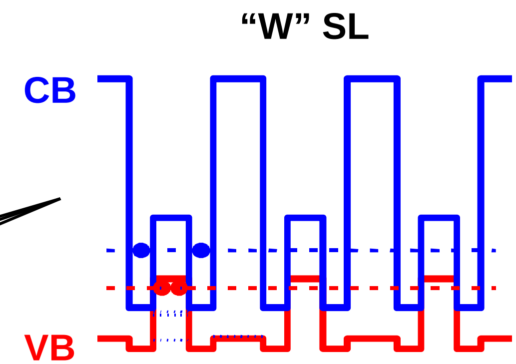
If design ***underestimates*** *actual p_{bg}, induced barrier blocks collection of photoexcited electrons until reverse bias is applied*

If design ***overestimates*** *p_{bg}, CB slopes too soon & narrow gap sees high internal field*



(C). INDEPENDENT CONTROL OVER CBO & VBO

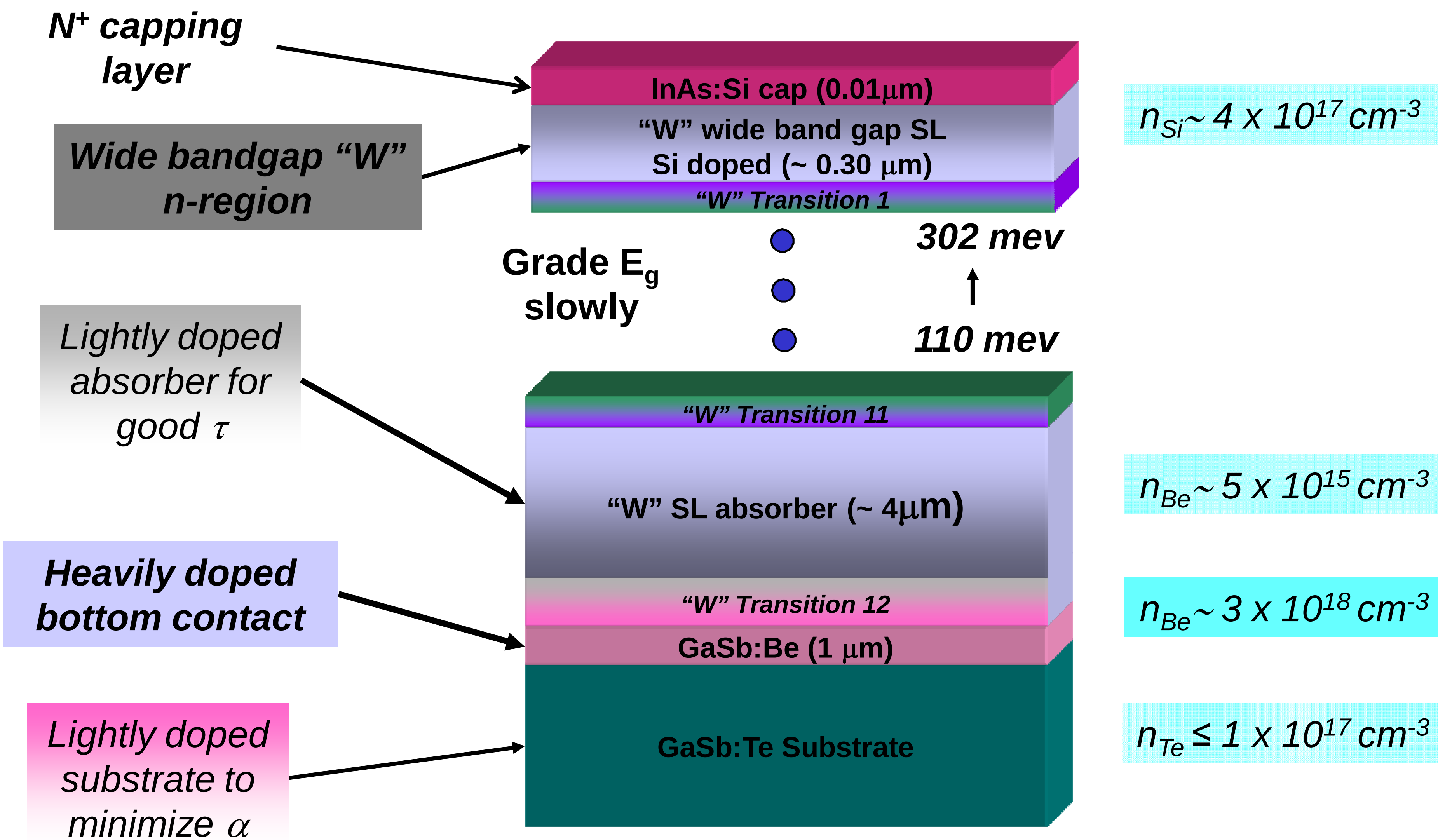




Each "W" region has different QW thicknesses (but fixed GaInSb & AlGaInSb alloy compositions)

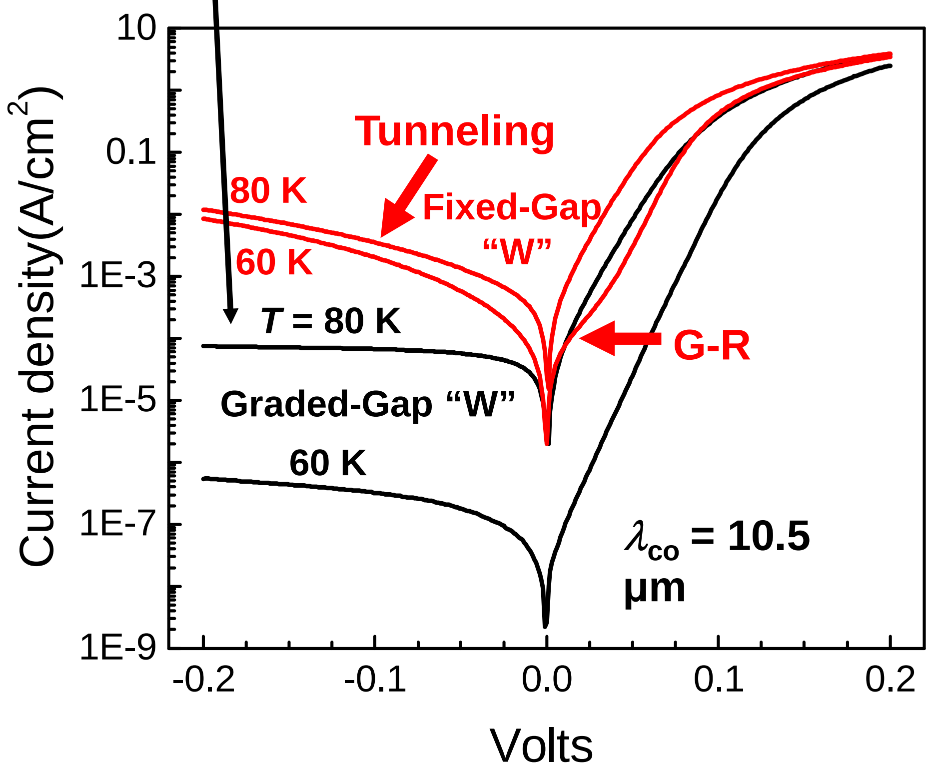
- *3 knobs (InAs, GaInSb, & AlGaInSb thicknesses) allow nearly independent control over CBO, E_g, & strain compensation (Impossible with 2-constituent SL or MCT)*
- *No need for challenging mid-growth variations of alloy composition*

Graded-Gap "W" Photodiode for Long-Wave Infrared Detection

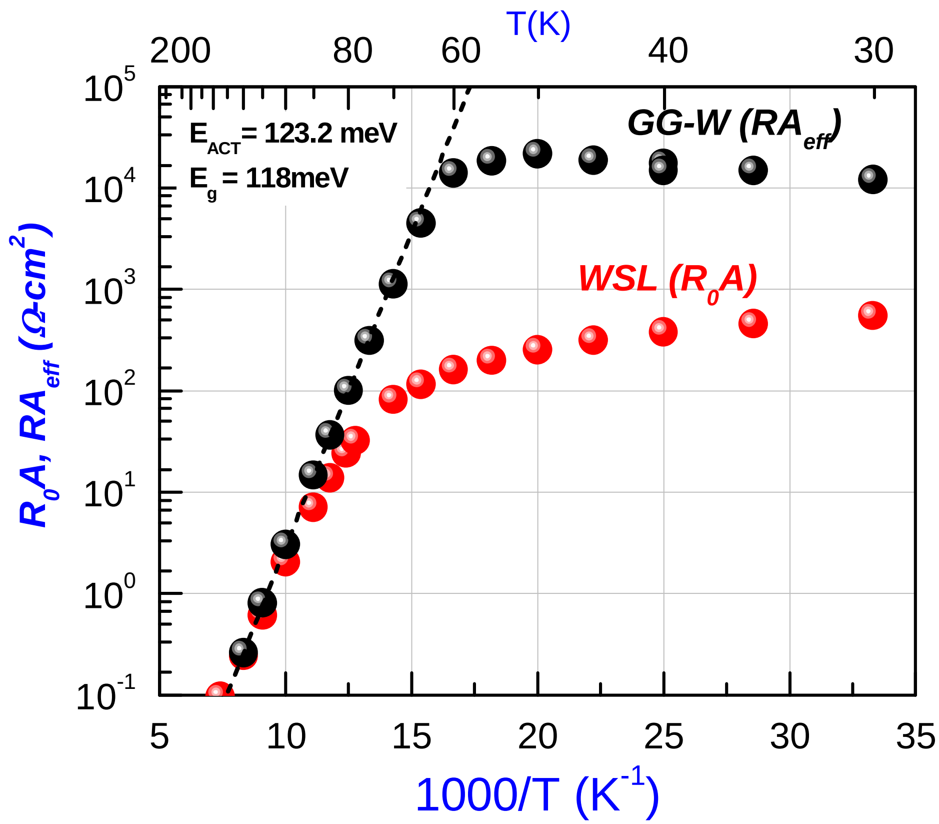


GG-W PHOTODIODES:
SUPPRESSED DARK CURRENTS & HIGH R_0A

Nearly-flat I-V implies strong suppression of tunneling, TAT, & G-R currents in GG-W

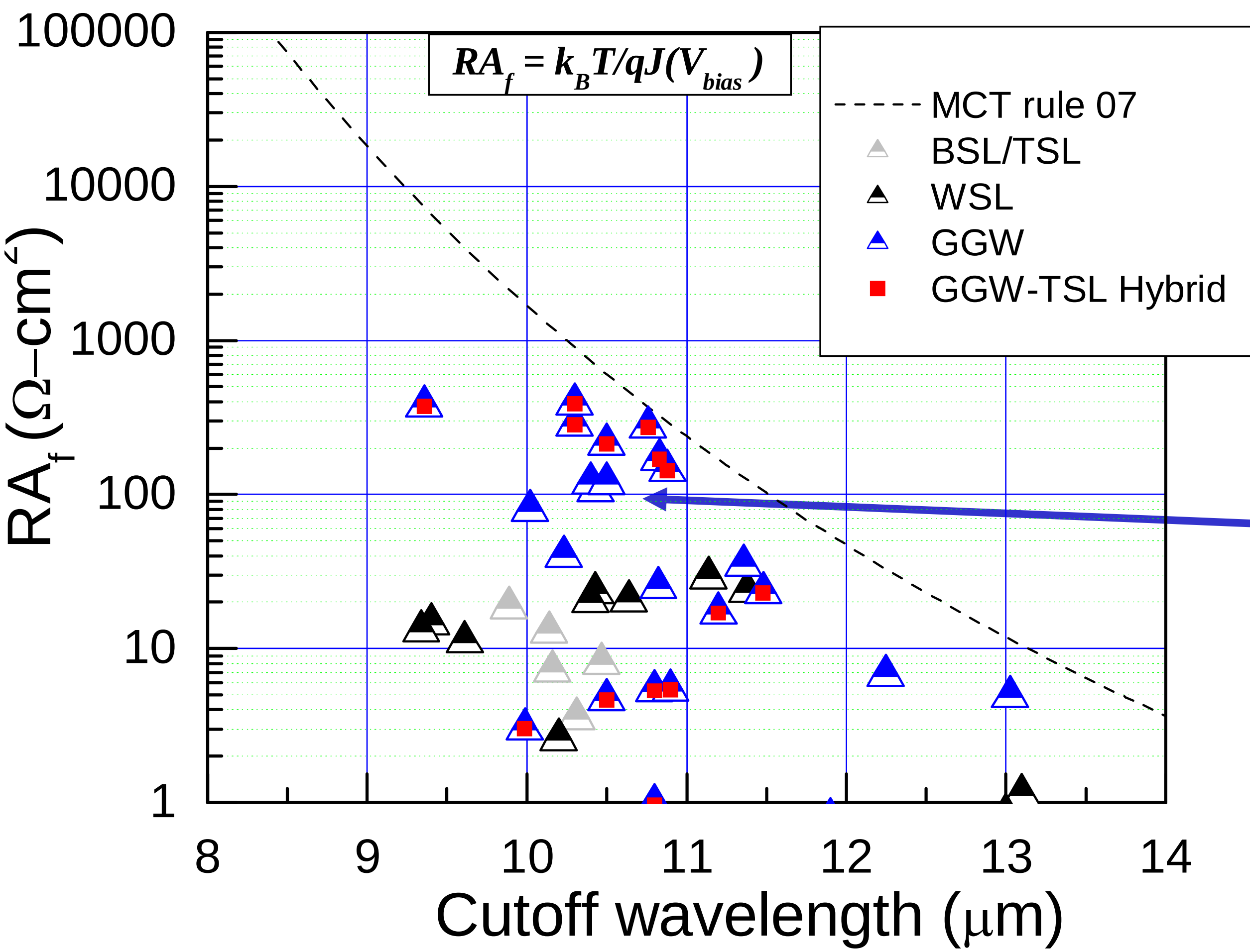


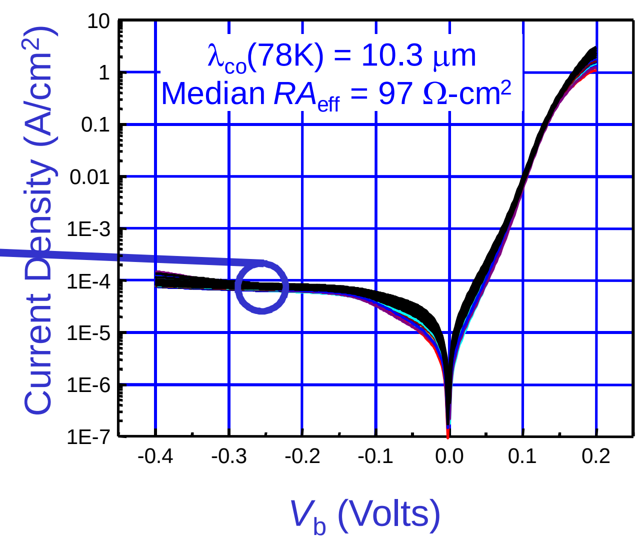
GGW diffusion limited well below 80K (Note use of $RA_{eff} = k_BT/qJ_{bias}$ for GG-W operating at non-zero V_{bias})



GG-W (RA_{eff}) vs. MCT

$$RA_{eff} \equiv \frac{kT}{qj_D}$$



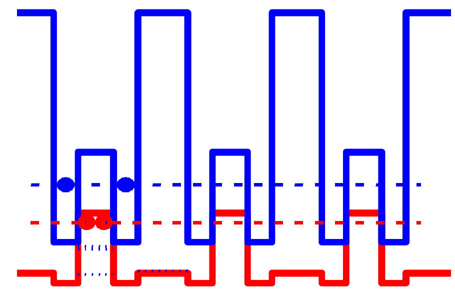


GG-diode results approach MCT rule07 – poised to move ahead

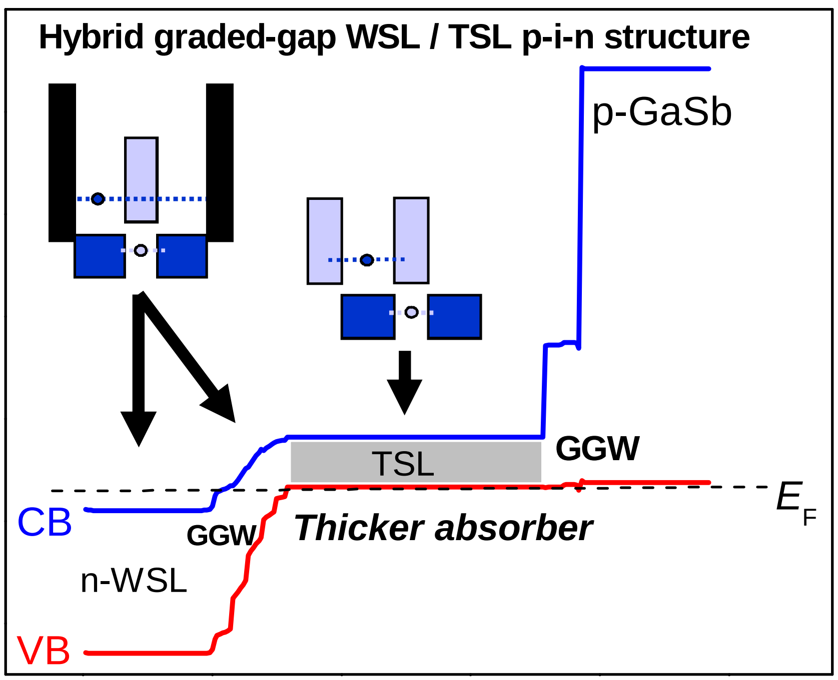
"W" LIMITATION – LOWER MOBILITY

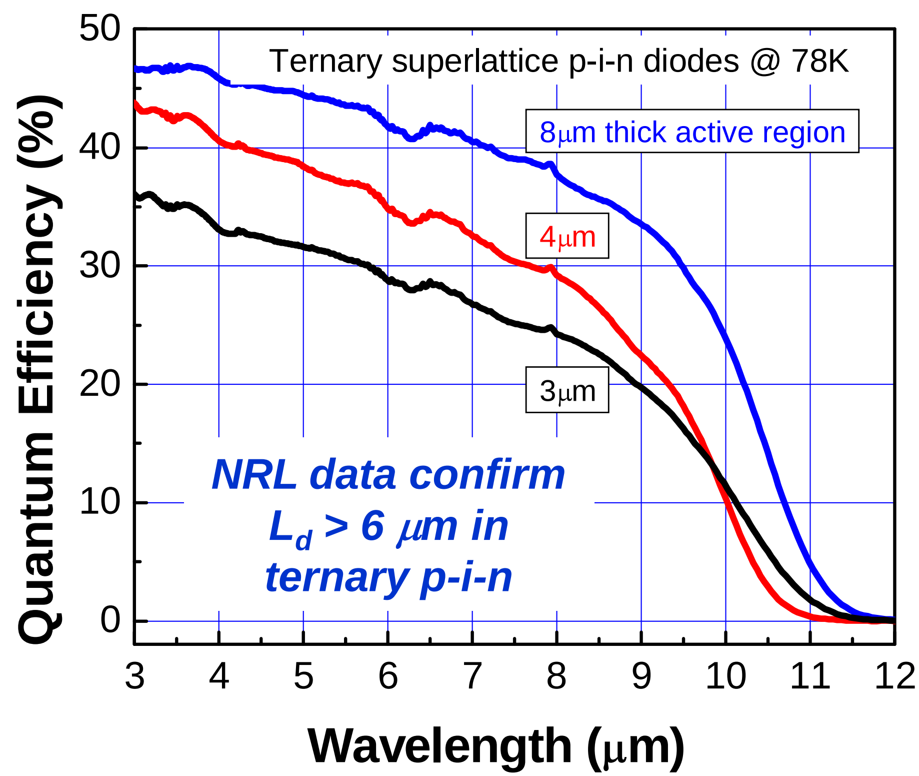
Larger m_{nz} in WSL suppresses tunneling, but with unwanted side-effect of decreasing mobility

Fix: Hybrid, with SL absorber but GG-W depletion region (Also reduces scattering by eliminating 2 interfaces per period, & eliminates Al-containing layers)



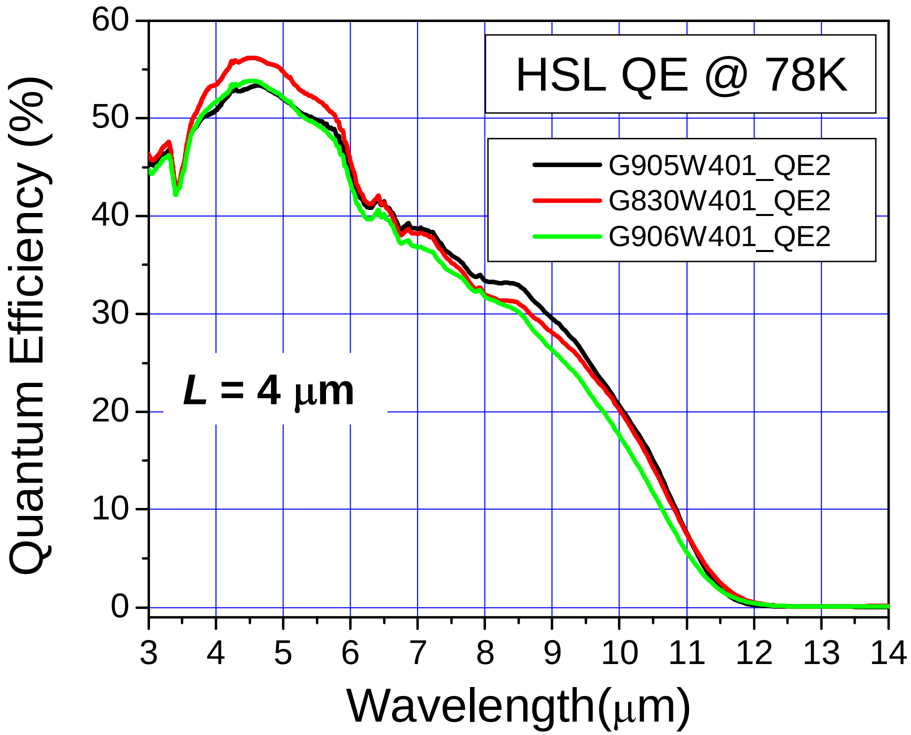
"W" SL



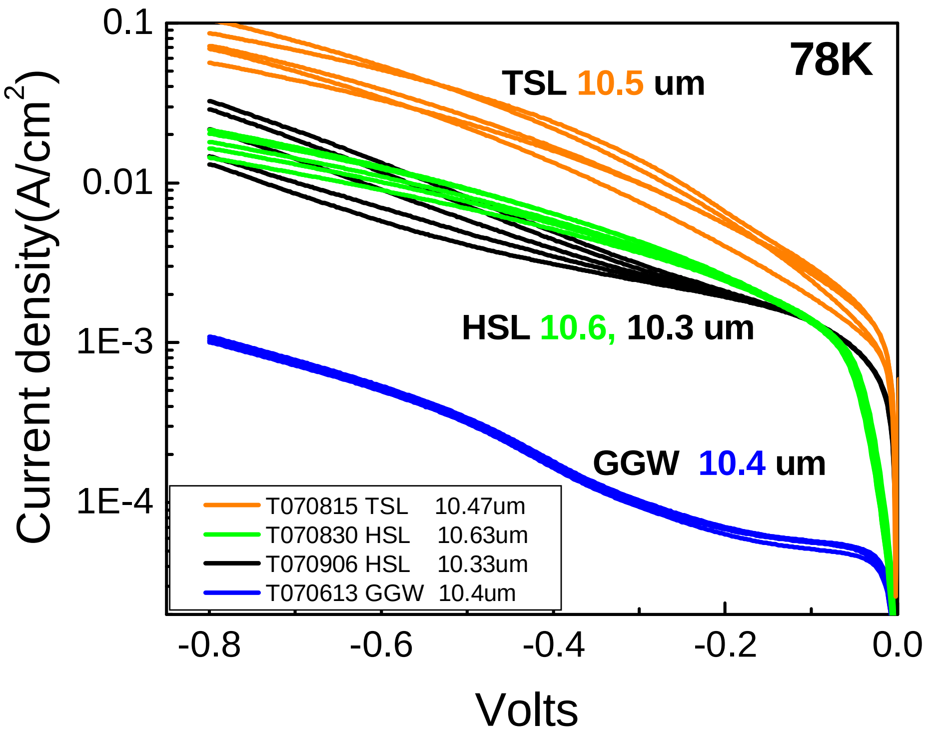


PRELIMINARY HYBRID SL PHOTODIODES

QE_{HSL} ~ 33% at 8μm (QE_{GGW} < 30 %)

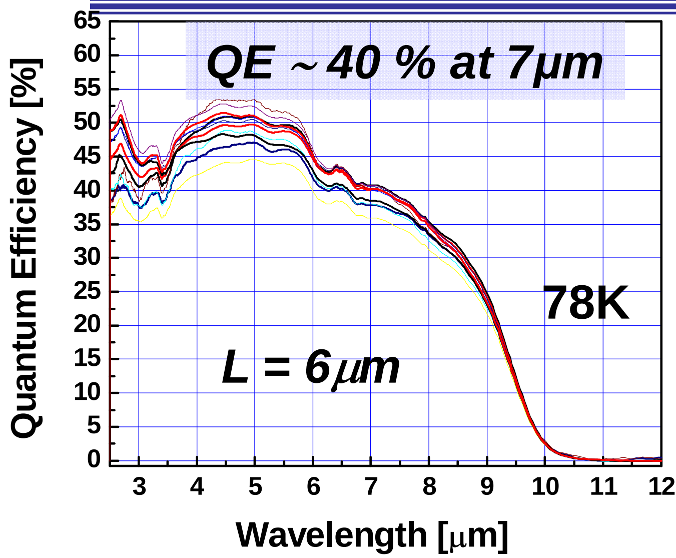


RA_{eff}(HSL) ~ 10 Ω-cm²
(factor of 10 lower than GG-W)



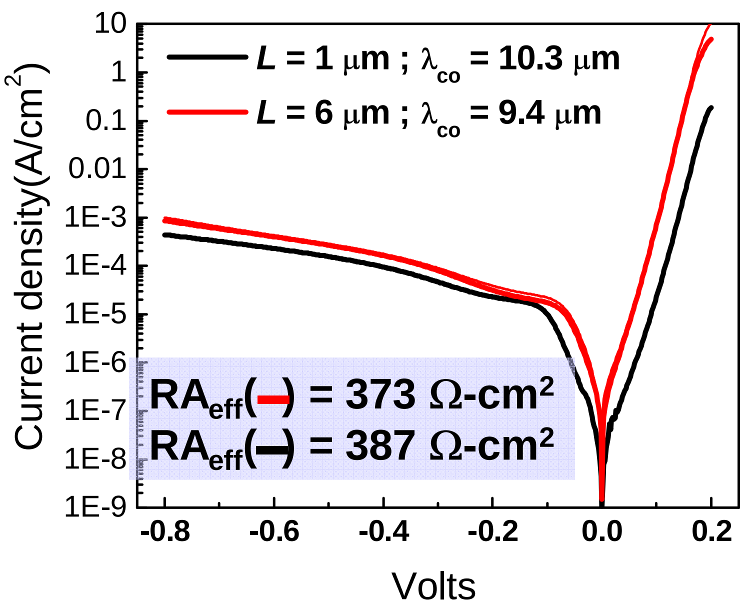
Initial hybrid structures yield higher QE than GG-W & lower dark current than TSLs, however QE is only marginally better and dark current characteristics inferior to GG-W

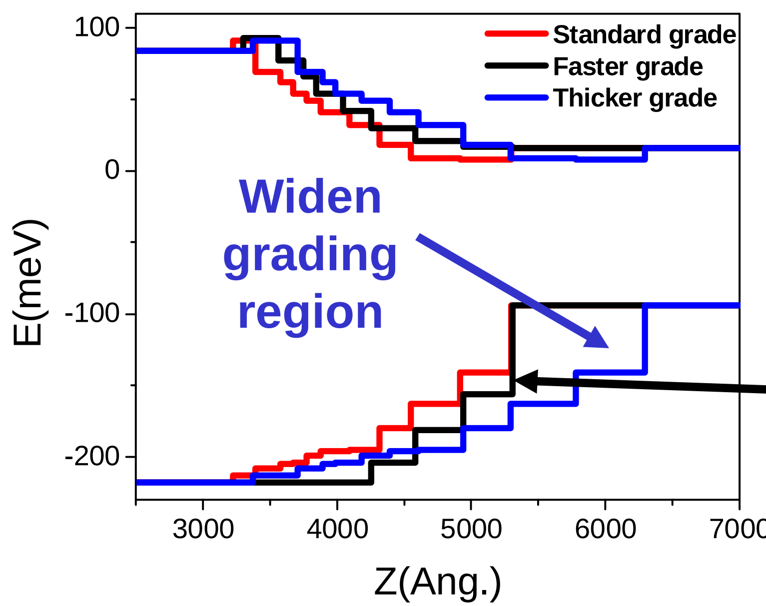
RECENT HYBRID SL PHOTODIODES



Recent hybrid structures also yield higher QE than GG-W with improved dark current characteristics due to improved designs

Thicker hole well in SL and refinement of bandgap grading for HSL

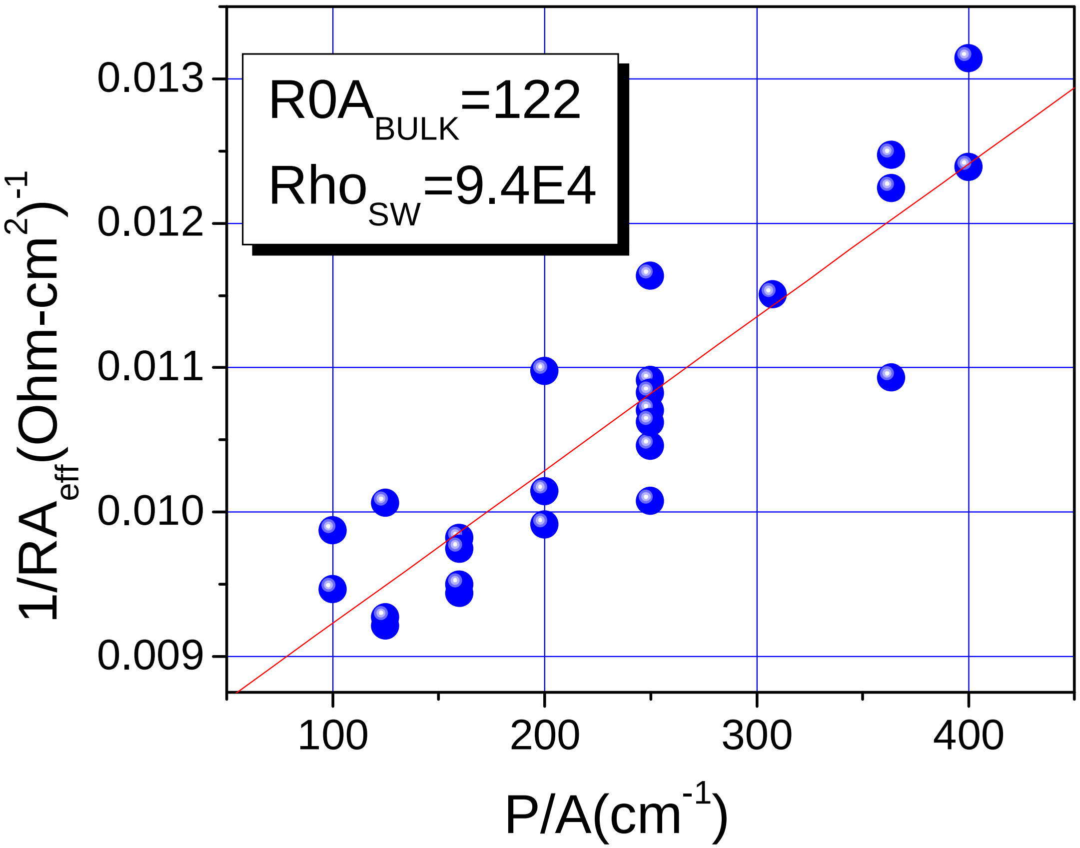


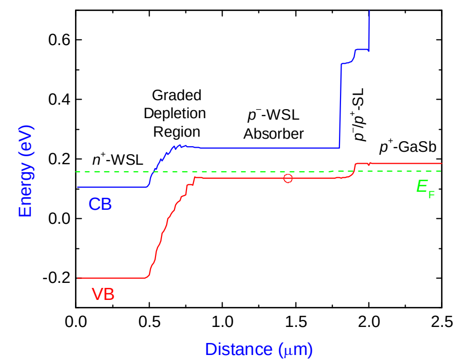


Push VB down more quickly

SURFACE CURRENT: ***SELF-PASSIVATION IN GG-W***

Sidewall resistivity extracted from R_0A dependence on Perimeter/Area ratio (D = 100-400 μm)





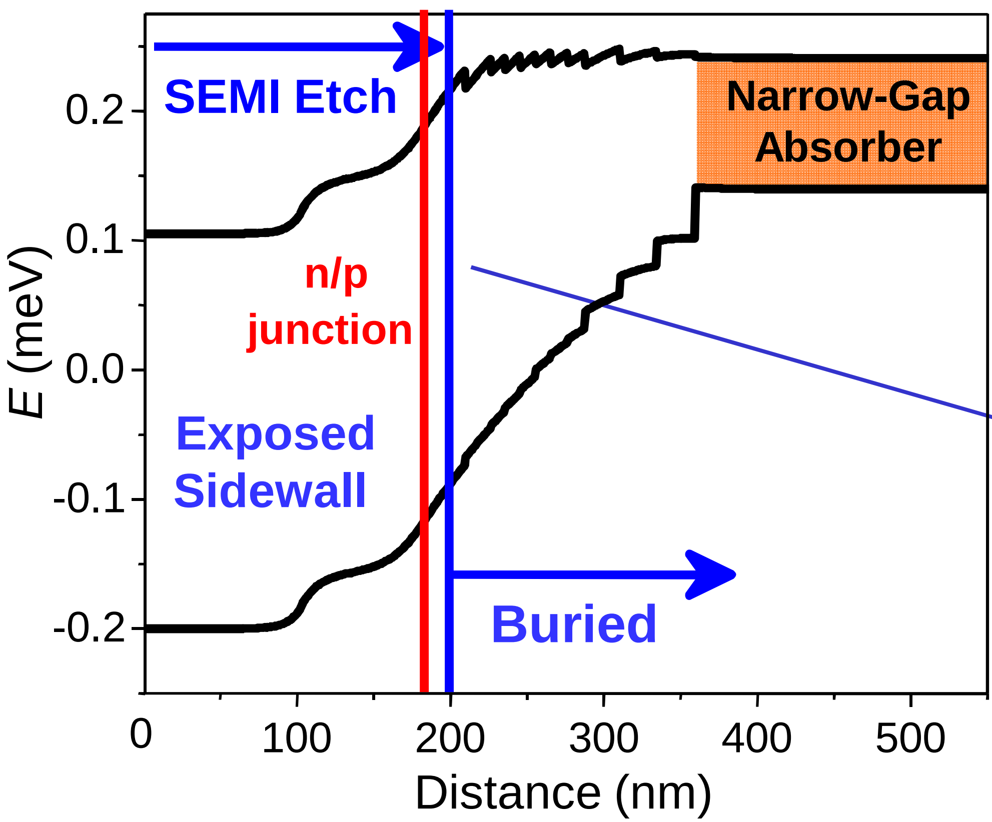
$\rho_{surface}$ = 4200 – 450,000 Ω-cm higher than for ANY earlier LWIR T2 results (both passivated & unpassivated), indicating self-passivation in GG-WSLs

But it's not enough

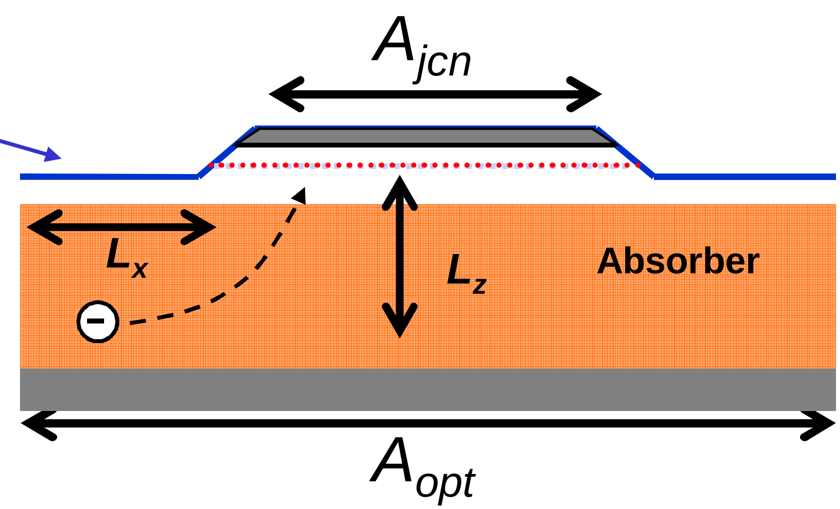
LOWERING THE PASSIVATION BAR:
SHALLOW-ETCH MESA ISOLATION (SEMI)

SEMI process, combined with GG-material, completely eliminates all exposure of narrow-gap regions to sidewalls

Passivation of wider-gap material much less challenging

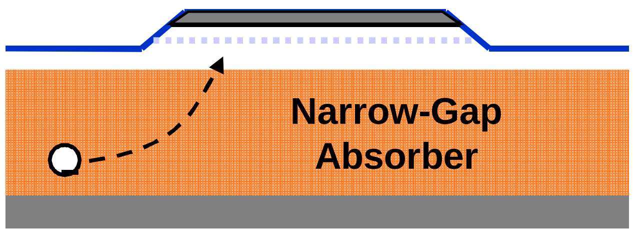


SEMI also allows 100% optical fill factor combined with reduced junction area, by relying on lateral diffusion of photoexcited carriers

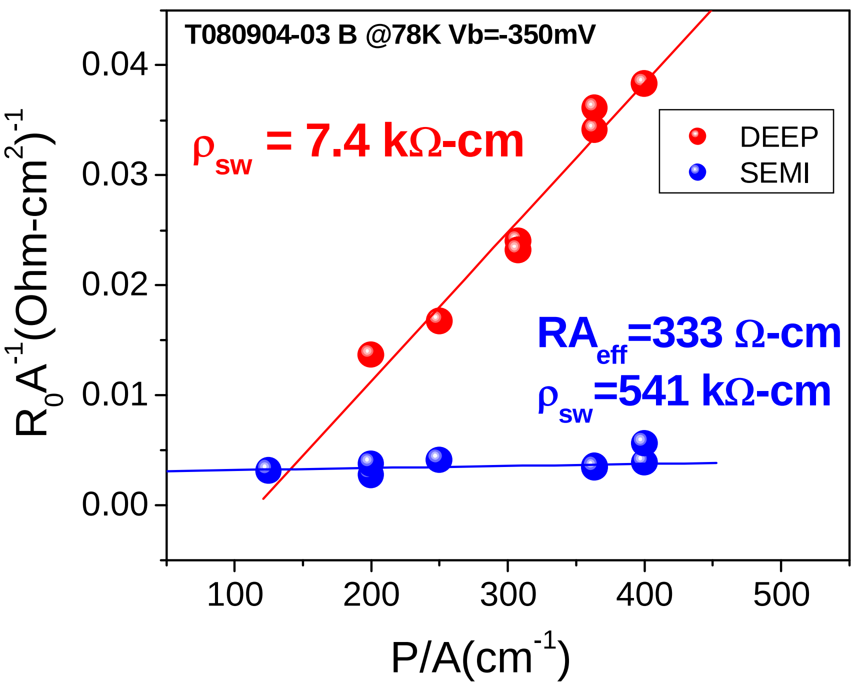


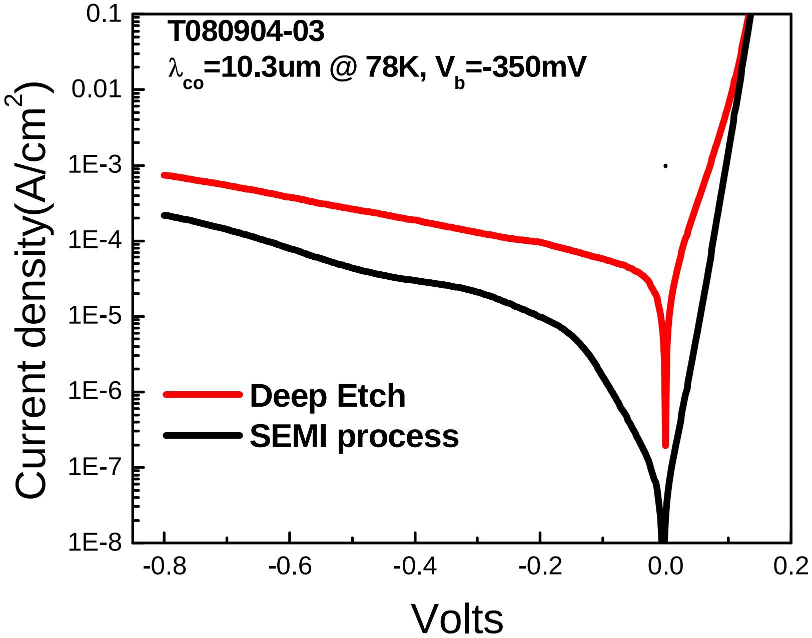
SEMI: EFFECTIVE SELF-PASSIVATION

Burying the narrow-gap region substantially increases the sidewall resistivity

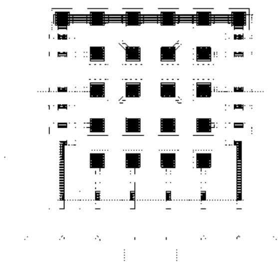


HSL photodetector with L = 1 μm





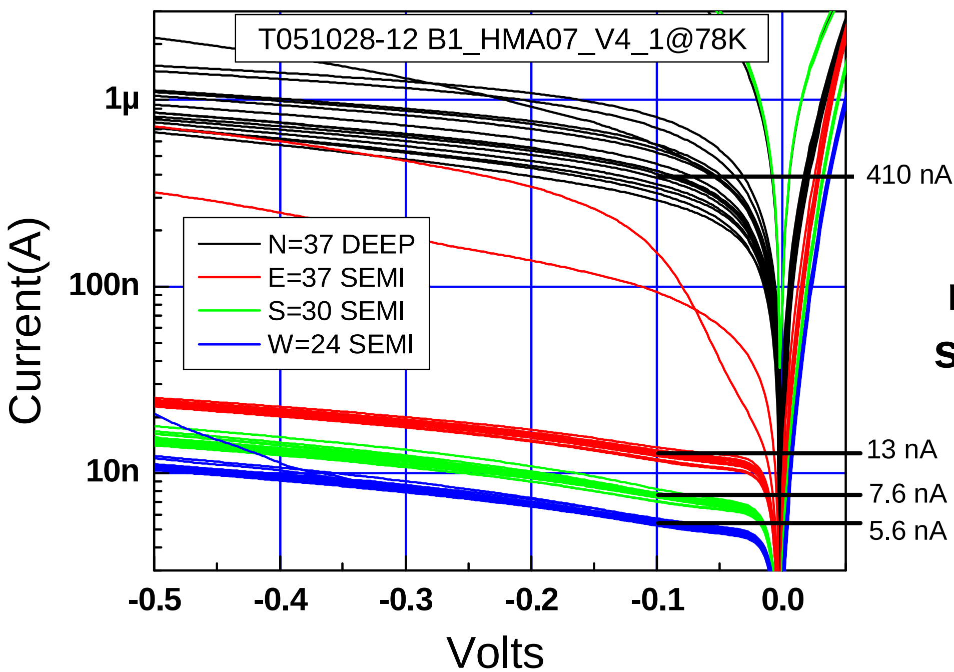
SEMI MINI-ARRAYS: LOWER SIDEWALL CURRENTS



4x4 Mini-Arrays
(40-μm pitch, Variable junction area)

process	Lmesa(um)	Amesa	Rmesa	Ipix(nA)	Ri
Deep	37	1369	1.0	410	31.5
SEMI	37	1369	1.0	13	1.0
SEMI	30	900	0.7	7.6	0.6
SEMI	24	576	0.4	5.6	0.4

SEMI dark current scales with junction area, while deep-etched array has much larger j_D

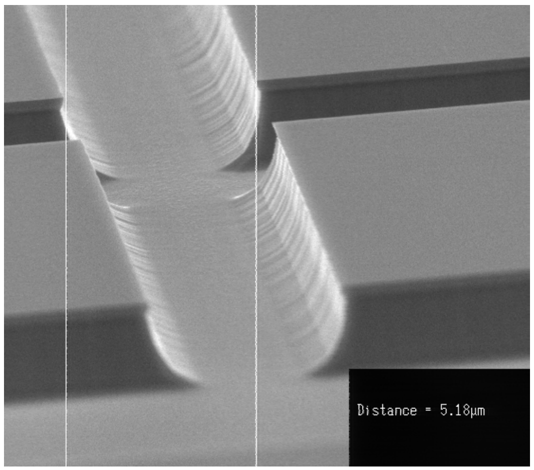


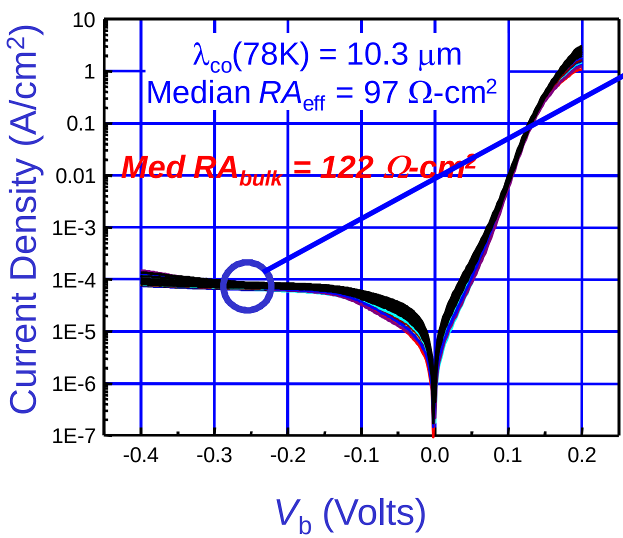
SEMI array shows 30x dark-current reduction *vs*. deep-etched array with same junction area (from same wafer)

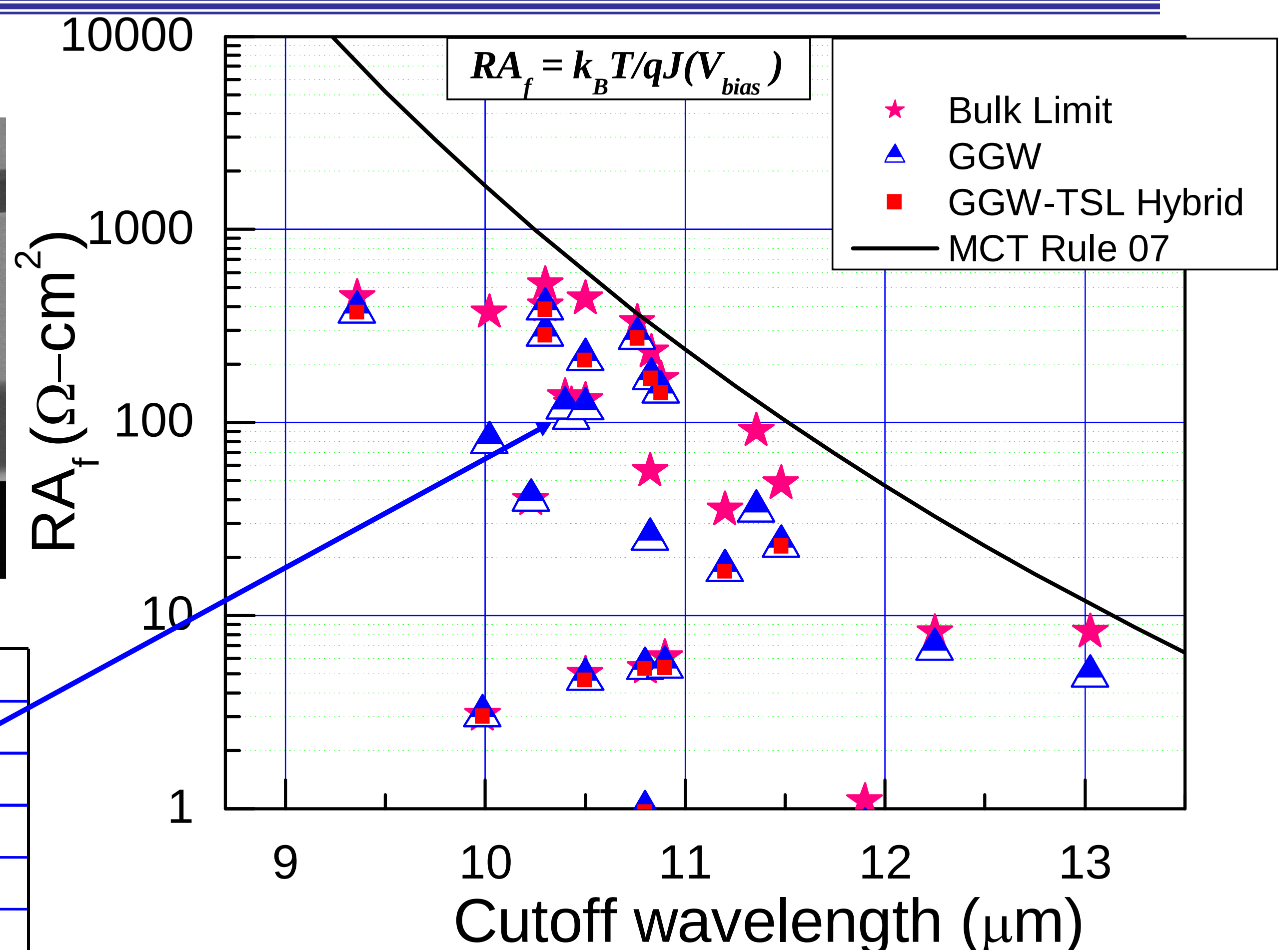
Also greater stability of characteristics over time

GG-structures – SEMI AND BULK LIMIT

Exposed mesa sidewalls

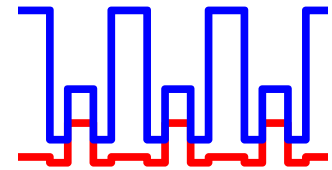




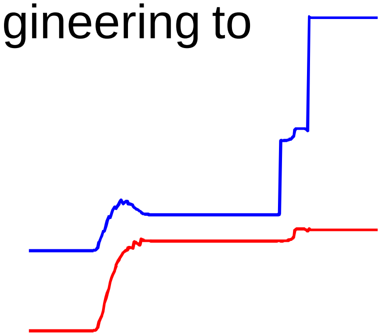


Using SEMI to suppress surface leakage then push further with graded doping in absorber for reduced J_D

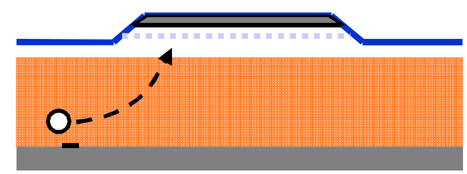
SUMMARY



- Long-λ detection is orders of magnitude more challenging – For best D^*, maximize QE & minimize various dark currents by using electronic/optical engineering to enhance: (1) absorption, (2) mobility, (3) lifetime, & (4) energy gap



- "W" SL combines 2D DOS for high α, large m_{nz} for suppressed tunneling, & flexible independent control over CBO & VBO
- Graded-gap "W" strongly suppresses tunneling & G-R currents
- Hybrid (SL absorber + GG-W depletion region) enhances QE ($L_d \geq 6$ μm) yet maintains good dark current characteristics
- Surface currents reduced:
  - (1) Increased E_g in depletion region of GG-diodes provides self-passivation
  - (2) Shallow-Etch Mesa Isolation (SEMI) + GG-diodes



    - Eliminates all narrow-gap exposure to etched sidewalls
    - Reduces junction area while maintaining 100% fill factor
    - Mini-array testing: Far lower surface dark currents (sometimes) & greater temporal stability than conventional deep etch

To beat MCT, still need to put all the pieces together!